IO'S INTERACTION WITH THE PLASMA TORUS: CURRENTS IN THE ALFVÉN WINGS AND JOULE HEATING

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1. Introduction

Soon after the discovery of the Io effect (modulation of the decameter (DAM) radiation) by Bigg in 1964, the first electrodynamic interaction models have been proposed by Piddington and Drake (1968), Goldreich and Lyndon–Bell (1969), Webster et al. (1972) and others. In these so–called current–loop–models the corotational electric field of Jupiter's magnetosphere drives currents through Io or its ionosphere. These currents are continued by field–aligned currents which flow toward Jupiter, then through Jupiter's ionosphere and back to Io as field–aligned currents on Io's side facing Jupiter (see Figure 1). The total current in this closed loop depends on the effective conductances of Io/Io's ionosphere (Σ_{Io}) and of that of Jupiter's ionosphere (Σ_{ψ}). In the model of Goertz and Deift (1973) the field–aligned currents are carried by linear Alfvén waves. These models are not valid when the travel time of an Alfvén wave from Io to Jupiter and back to Io becomes longer than the time the plasma needs to pass Io. Even after the Pioneer encounters in 1973 one had expected low plasma mass densities in Jupiter's magnetosphere and therefore large Alfvén velocities

$$v_A = \frac{B}{\sqrt{\mu_0 \rho}} \tag{1}$$

(where B is the magnetic field strength, μ_0 is the magnetic permeability of free space, and ρ is the plasma mass density) and short travel times.

The Io plasma torus was discovered by Kupo et al. in 1976 by earth–based observations and later studied in situ by the Voyager spacecraft in 1979. Due to the high number densities of heavy ions (mostly oxygen and sulfur in various charge states), the Alfvén speed becomes as low as 250 km/s in the center of the torus at Io's orbit (Bagenal and Sullivan, 1981) and the travel times are larger than the passing times even when Io is located near the torus boundary (Bagenal, 1983).

In connection with the interpretation of magnetic field perturbations observed by Voyager 1 near Io (Ness et al., 1979), Neubauer (1980) has given a new description of the interaction in terms of the generation of standing nonlinear Alfvén waves. Compared to the current–loop and linear Alfvén wave models, the nonlinear Alfvén wave model shows two essentially new features:

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1.) Jupiter's ionosphere has no direct influence (via Σ_ψ) on the currents; instead the Alfvén wave conductance

$$\Sigma_A = \frac{1}{\mu_0 v_0 \sqrt{1+M_A^2}} \tag{2}$$

(v_0 is the unperturbed plasma velocity, $M_A = v_0/v_A$ is the Alfvénic Mach number) limits the magnitude of the total current through Io's ionosphere.

2.) in the nonlinear case the Alfvén wave propagates obliquely to the unperturbed magnetic field at an angle

$$\theta_A = \arctan(M_A) \tag{3}$$

independent of the strength of the Alfvén wave.

Neubauer's (1980) analytic solution of the nonlinear MHD–equations is valid outside a certain distance away from Io where all quantities are assumed to be independent of the coordinate z parallel to the Alfvén characteristics (wing axis).

In the numerical models of Luzemann (1980) and Herbert (1985) Alfvén waves have been included.

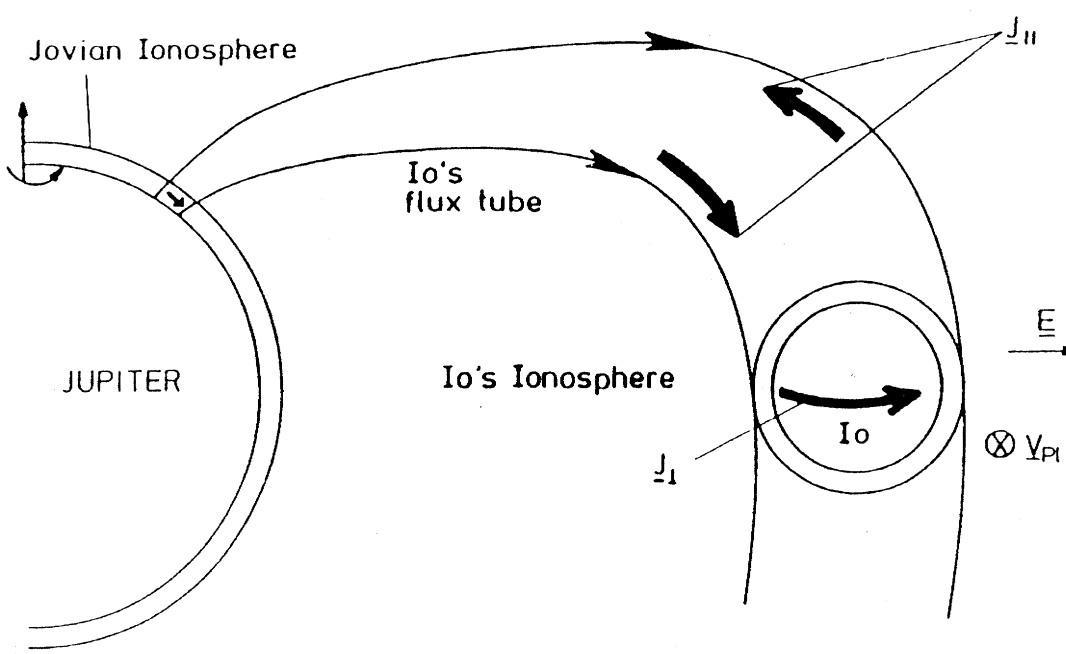

Fig. 1: Io's interaction: current–loop–models (see text) (Luzemann, 1980).

2. The model

We have developed a three dimensional model of the interaction between Io and the plasma torus, which allows us to calculate the electric fields, the current density distributions and the magnetic fields in Io's vicinity and in the Alfvén wings. A full description of the model and many results can be found in Wolf–Gladrow et al. (1987). In the following we will address only some essential features of the model without discussing the treatment of the equations and their numerical solutions. Figure 2 shows a sketch of the interaction region. The unperturbed plasma has a speed of 57 km/s, a southward directed field of 1900 nT, and an electron number density of the order of 10^9 m^{-3}. The flow is subalfvénic (Alfvénic Mach number $M_A < 1$), supersonic (sonic Mach number $M_S > 1$), and subfast (fast Mach number $M_f < 1$). As expected for a subfast flow no bow shock has been observed at the Voyager 1 fly–by near Io. Note that Io's Mach number regime is quite different compared to the flows at other non–magnetized bodies in the solar system. At Venus and comets in the solar wind ($M_A > 1$, $M_S > 1$, $M_f > 1$) bow shocks and magnetic tails have been observed (e.g. Russel et al., 1979a,b; Smith, E.J. et al., 1986; Neubauer et al., 1986). A magnetic tail was observed when Titan was located in the magnetosphere of Saturn ($M_A > 1$, $M_S < 1$, $M_f < 1$; Ness et al., 1981; Neubauer et al., 1984). At low Alfvénic Mach numbers ($M_A = 0.15$ according to Acuña et al., 1981) and a relatively low density atmosphere one would expect only a slight draping on the magnetic field lines (the tilt angle is of the order of $\theta_A = \arctan(M_A)$) and no formation of a magnetic tail.

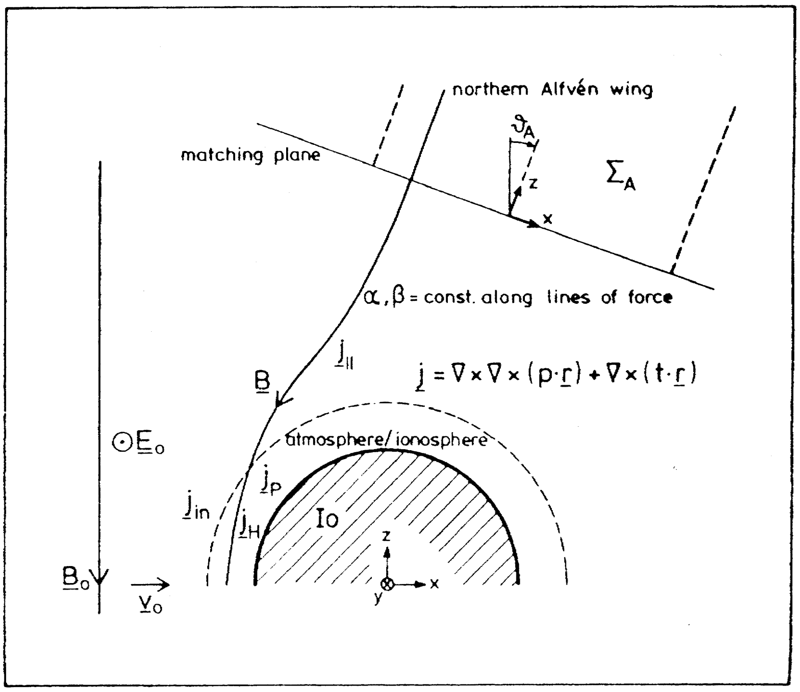

Fig. 2: Geometry of the interaction region: the unperturbed corotating plasma enters from the left; Pedersen and Hall currents in Io's ionosphere; inertial and field–aligned currents; draping of magnetic field lines; Alfvén wings; Euler potentials; poloidal and toroidal fields; definition of coordinate systems.

The corotational electric field seen in Io's rest frame

$$\underline{E}_0 = -\underline{v}_0 \times \underline{B}_0 \tag{4}$$

drives Pedersen and Hall currents through Io's ionosphere. These currents are continued by field–aligned currents flowing up in the northern Alfvén–wing in Io's side away from Jupiter respectively down from the northern Alfvén–wing on Io's side facing Jupiter (see Figure 2). The applied electric field will be perturbed due to the presence of the conductive body (Io's ionosphere), and the magnetic field will be modified ("draping") due to the currents.

In the linear case, the propagation of the Alfvén waves along the magnetic field may be compared with the propagation of shear waves along the strings of a harp, for example. In the case of Io, the Alfvén waves are nonlinear. These waves propagate strictly along the magnetic field in the plasma rest frame and transport energy over large distances without spatial attenuation, whereas the amplitudes of the other MHD–modes, e.g. slow and fast magneto–acoustic waves, decrease rapidly because their energy spreads out over a finite space–angle. As input the model needs parameters which describe the upstream plasma (velocity, magnetic field, number densities) and the neutral gas and the plasma density distributions in Io's atmosphere/ionosphere (Table 1; see Wolf–Gladrow et al. (1987) for details).

Atmosphere	$N_n(r) = N_{n,0} \cdot \exp(-(r - r_{Io})/H)$	
	$N_{n,0} = 6 \cdot 10^{16} cm^{-3}$	
	H = 120 km	
Ionosphere	N_e	spherically symmetric
	$N_{e,max} = 7.6 \cdot 10^9 m^{-3}$	
	$\nu_i / N_n = 2 \cdot 10^{-16} m^3/s$	(Webster et al., 1972)
	$\nu_e / N_n = 1.4 \cdot 10^{-15} m^3/s$	(Webster et al., 1972)
Upstream Plasma	B_0 = 1900 nT	
	v_0 = 57 km/s	in Io's rest frame
	E_0 = 0.108 V/m	in Io's rest frame
	m_i = 8 amu	
	$\rho_0 = 11900 amu/cm^3$	
	$N_{e,\infty} = 1490 cm^{-3}$	
	$M_A = 0.15$	
	$M_S = 1.8$	
Alfvén Wings	$\theta_A = 8.5°$	
	Σ_A = 2.0 S	

Table 1: Properties of Model 1

3. Results

First, we will present some results of a model with a spherically symmetric atmosphere (neutral surface density of $6{\cdot}10^{16}\mathrm{m}^{-3}$, scale height 120 km) and a spherical symmetric electron density in the ionosphere. Figure 3 shows the variations with height of the Pedersen and Hall conductivities in Io's ionosphere. Note that due to the low neutral gas density in the atmosphere the Hall conductivity is always lower than the Pedersen conductivity.

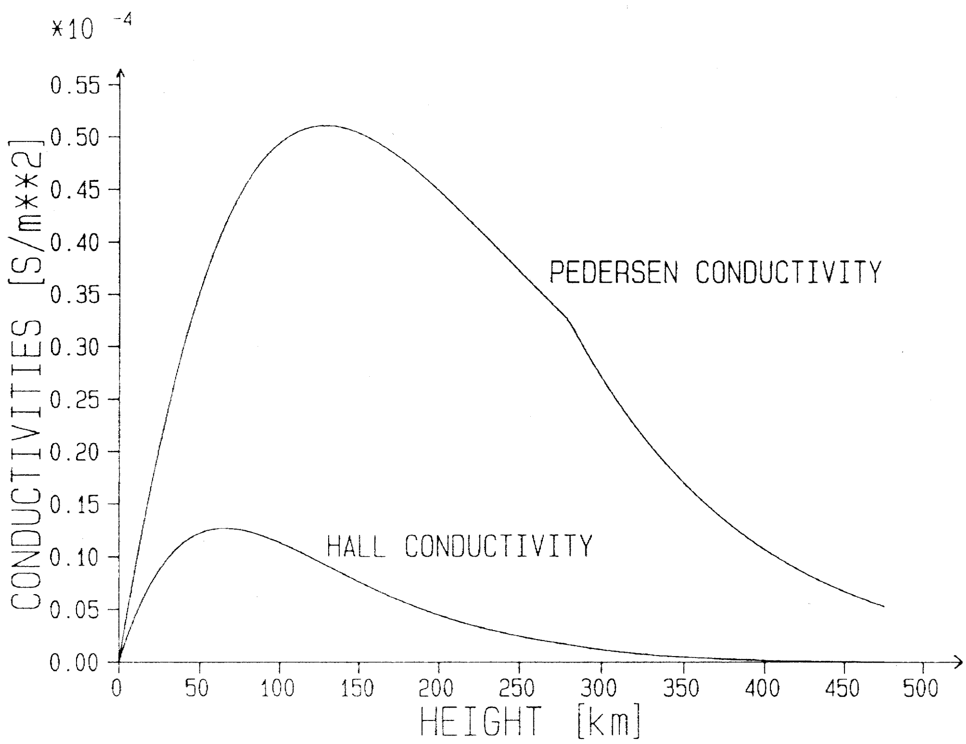

Fig. 3: Pedersen and Hall conductivities in Io's ionosphere (model 1, spherically symmetric)

Figure 4 shows the electric field in the equatorial plane of Io. Due to the conductive ionosphere the applied electric field decreases along the stagnation line and deep inside the ionosphere by more than a factor of 5. At the flanks you will observe an increase by a factor of 2.

This electric field drives Pedersen and Hall currents through Io's ionosphere (see Figure 5). These currents, which are perpendicular to the magnetic field, are continued by field–aligned currents. These are shown (Figure 6) in a meridional plane where we look from downstream toward Io. In Figure 7, these same currents are shown in a slice through the northern Alfvén wing. You will observe currents flowing toward Io on the side facing Jupiter and currents flowing away from Io on the opposite side. From the maximum value of the parallel current density ($\approx 10^{-6}$ A/m^2) one can derive a maximum value of the parallel velocity difference between electrons and ions of the order of 10 km/s in the inner torus.

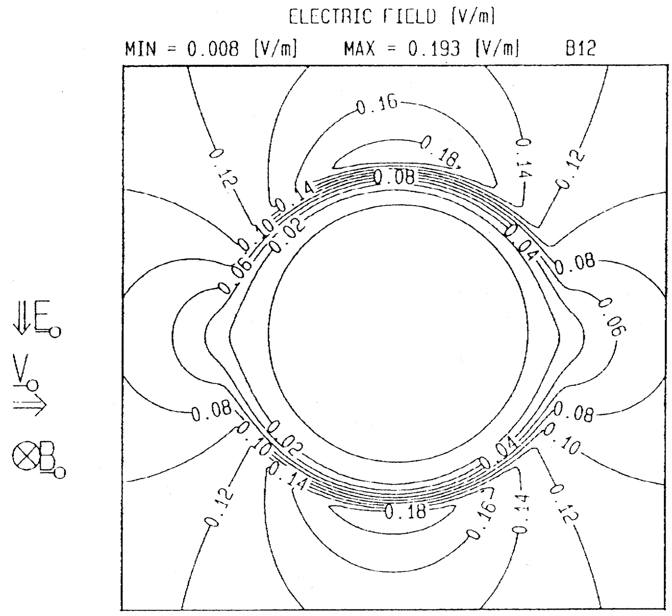

Fig. 4: Contours of electric field magnitude in the equatorial plane of Io (model 1). The disturbances caused by the thin conductive ionosphere (some 100 km) reach far out (some 1000 km). One observes near symmetry between upstream and downstream for this spherical symmetric atmosphere/ionosphere.

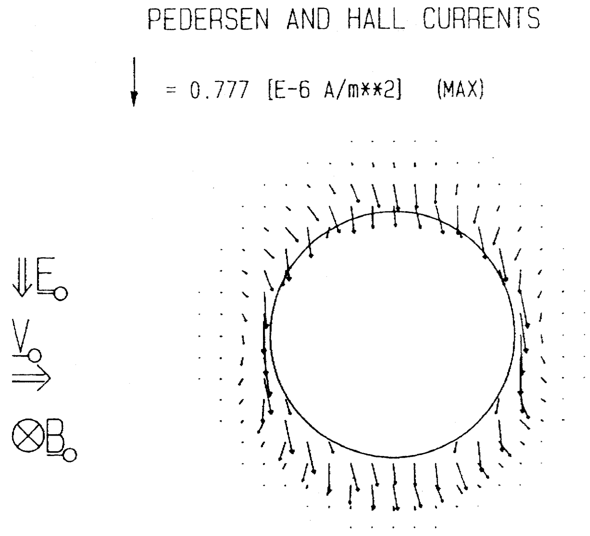

Fig. 5: Pedersen and Hall currents in the equatorial plane (model 1) with a peak value of 8×10^{-7} A/m^2.

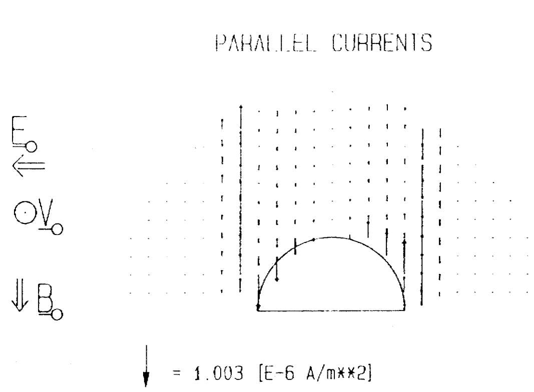

Fig. 6: Field–aligned currents in the y–z plane viewed from downstream (model 1): on Io's side facing Jupiter (on the right), currents flow generally down from the northern Alfvén wing into the ionosphere and convert into perpendicular currents (not shown in this picture) which traverse the ionosphere and flow out of the ionosphere on the opposite side as field–aligned currents again. Only a small part of the currents near Io's surface which flow against the "main direction" on each side reaches the northern Alfvén wing.

The magnitude of the magnetic field in the equatorial plane is shown in Figure 8. The unperturbed field amounts to 1900nT. We observe an increase by more than 200 nT in an upstream region and a decrease by more than 300 nT in a downstream region. Qualitatively, such a behavior can be explained by the simple draping model which Alfvén (1957) has proposed 30 years ago in the context of the interaction between comets and the solar wind.

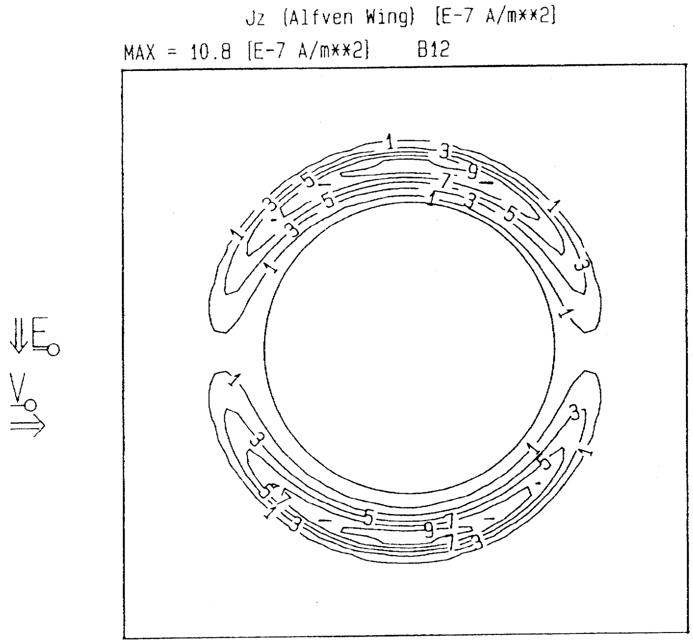

Fig. 7: Contours of the current density parallel to the Alfvén characteristic in a slice through the northern Alfvén wing (model 1): on Io's side facing Jupiter (upper part), currents flow down to Io's ionosphere and on the opposite side from Io into the northern wing. These currents are nearly field–aligned so that the comparison with Figure 8 is meaningful.

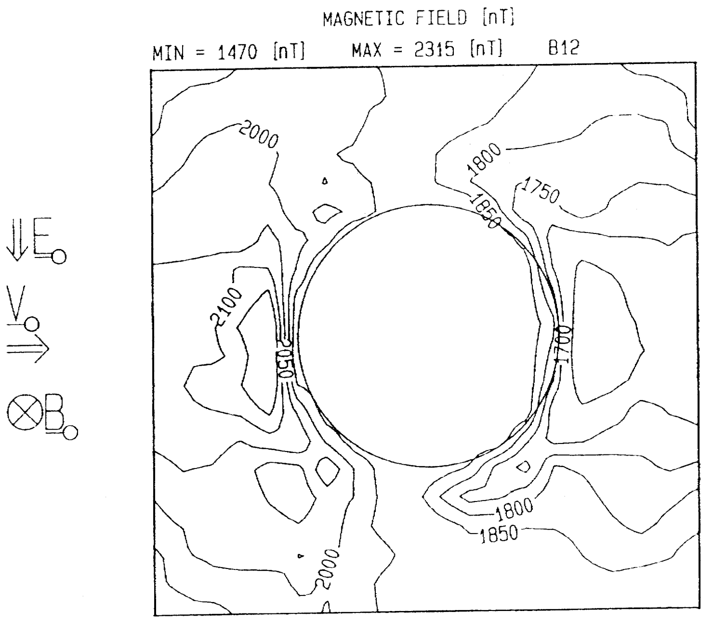

Fig. 8: Contours of the magnetic field in the equatorial plane (model 1): unperturbed field magnitude B_0 = 1900 nT; magnitude is increased upstream and decreased downstream.

As a further step toward more realistic models we have introduced a somewhat more complicated conductivity distribution. In the second model the conductivity has a maximum in the upstream region. Thus the electric field decreases stronger upstream than downstream as expected (Figure 9). The currents in the Alfvén wing look pretty much like in the spherical symmetric model. Only the magnitudes are somewhat reduced due to the lower conductance. In the third model the conductivity has its maximum at the flank on the side away from Jupiter. Again the symmetry of the electric field is perturbed in the expected sense (Figure 10). In this case the currents in the Alfvén wings show a small but clear asymmetry (Figure 11).

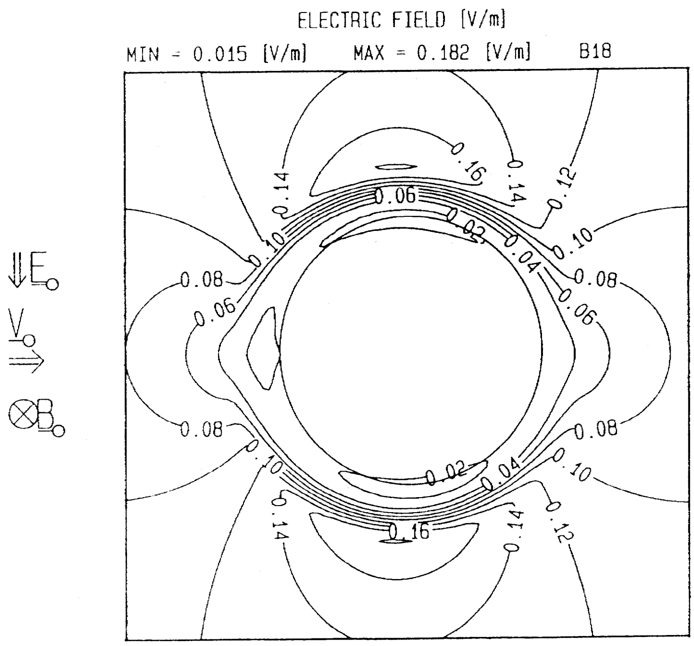

Fig. 9: Contours of the electric field magnitude in the equatorial plane of Io (model 2): the field strength in the low conductive region downstream is higher than in the upstream region.

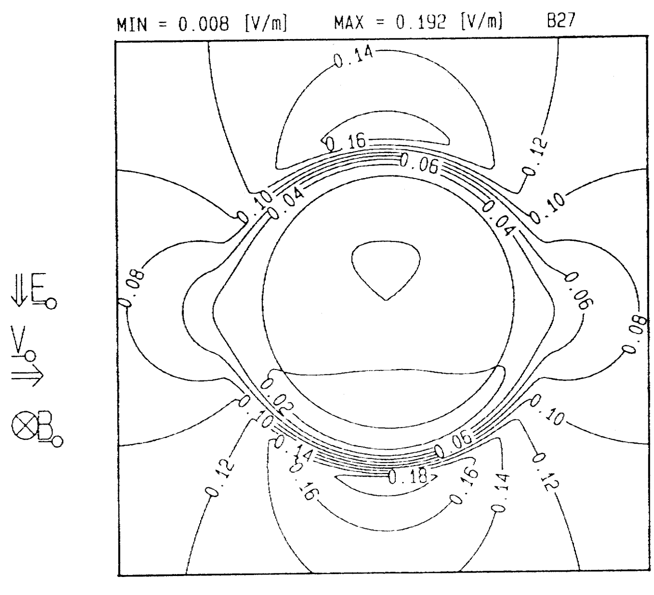

Fig. 10: Contours of the electric field magnitude in the equatorial plane of Io (model 3): the field strength shows a minimum in the high conductive region at the lower flank.

An interesting feature is the occurrence of "reverse currents", e.g. currents which flow in the opposite direction/antiparallel to the main currents (in the banana–shaped regions) in the Alfvén wings. These currents may be observed in models with small neutral scale heights (which means large conductivity gradients). Figure 12 shows the current distribution in the northern Alfvén wing for a scale height of 60 km. These "reverse currents" may be of some interest in the context of the generation of DAM via certain plasma instabilities (Goldstein and Goertz, 1983).

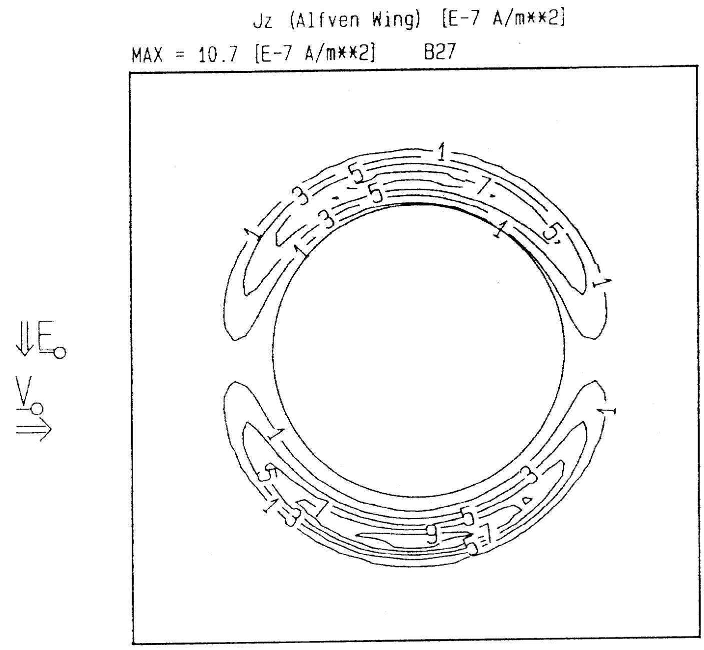

Fig. 11: Same as Figure 7, but model 3. One may observe a slight asymmetry between the currents on the two flanks.

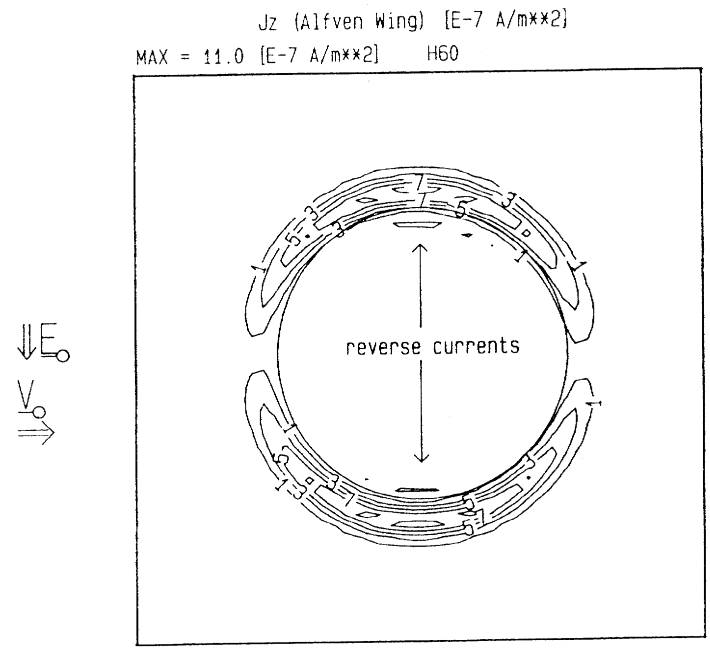

Fig. 12: Same as Figure 7, but model 4 (small scale height): reverse currents (see text).

As the last point we will address Joule–heating. By integration of the Joule–heating rate over the whole volume of Io's atmosphere we found a value of $3–4{\cdot}10^{11}$ W. This heat source is especially important in the upstream region at heights lower than 100 km, at the flanks around 500 km and on the nightside of Io. These heat–source must be included in atmospheric models (this has not been done yet, as far as we know). We would expect much higher neutral temperatures and therefore a more extended atmosphere. But this has to be investigated in a coupled atmosphere–interaction model.

4. Summary

We have presented results of a three dimensional MHD–model of Io's interaction with the plasma torus. The main results are:

- the electric field magnitude decreases by more than a factor of 5 in Io's ionosphere and along the stagnation line
- it increases by a factor of up to 2 at the flanks
- the maximum perpendicular and parallel current densities are of the order of 10^{-6} A/m^2
- the field–aligned velocity difference between electrons and ions is of the order of 10 km/s
- in models with small neutral scale height (high conductivity gradients) "reverse currents" occur
- Joule heating amounts to $3{\cdot}10^{11}$ W. This is an important energy source for Io's atmosphere and should be included in atmospheric models.